

Resolving the J/ψ RHIC puzzles at LHC

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Abstract. Experiments with gold-gold collisions at RHIC have revealed (i) stronger suppression of charmonium production at forward rapidity than at midrapidity and (ii) the similarity between the suppression degrees at RHIC and SPS energies. To describe these findings we employ the model that includes nuclear shadowing effects, calculated within the Glauber-Gribov theory, rapidity-dependent absorptive mechanism, caused by energy-momentum conservation, and dissociation and recombination of the charmonium due to interaction with co-moving matter. The free parameters of the model are tuned and fixed by comparison with experimental data at lower energies. A good agreement with the RHIC results concerning the rapidity and centrality distributions is obtained for both heavy $Au+Au$ and light $Cu+Cu$ colliding system. For pA and $A+A$ collisions at LHC the model predicts stronger suppression of the charmonium and bottomonium yields in stark contrast to thermal model predictions.

1. Introduction

The investigation of nuclear matter under extreme temperatures and densities, and the search for a predicted transition to a deconfined phase of quarks and gluons, the so-called Quark-Gluon Plasma (QGP), is one of the main goals of heavy-ion experiments at ultrarelativistic energies. Both theorists and experimentalists are looking for genuine QGP fingerprints, that cannot be masked or washed out by processes on a hadronic level. Charmonium was proposed about two decades ago [1] as one of the most promising QGP messengers because its yield would be significantly suppressed due to color Debye screening in the plasma phase. Also, due to the small interaction cross section of J/ψ in hadronic matter, charmonium spectrum is expected to carry information about the early hot and dense stage of nuclear collision. Since the volume of the produced QGP depends on the collision energy, centrality and mass of colliding nuclei, it is generally believed that the suppression of the J/ψ yield would increase with rise of the aforementioned factors.

Therefore, the PHENIX measurement of the nuclear modification factor of charmonium at top RHIC energy $\sqrt{s} = 200$ AGeV [2] uncovered at least two unexpected features. Firstly, compared to charmonium suppression in lead-lead

collisions at SPS energy $E_{lab} = 160$ AGeV [3] the level of suppression at midrapidity at RHIC was found to be quite similar for the same number of participants despite the order of magnitude difference in center-of-mass energies of heavy-ion collisions. Secondly, J/ψ suppression increases unambiguously with rising rapidity, whereas the highest energy density and the most dense medium should be produced at $y = 0$. These findings, as well as the experimental results for dAu collisions, where the plasma formation is very unlikely, attract the attention to the whole variety of the processes, including both initial and final state effects, that are responsible for the charmonium production and its propagation through hot and dense medium.

The paper is organized as follows. Section 2 presents a description of the model that contains a comprehensive treatment of initial-state nuclear effects, such as nuclear shadowing and nuclear absorption, and final state interactions with the co-moving matter. Comparison with the available experimental data and predictions for $Pb + Pb$ collisions at LHC energy is given in Sec. 3. Finally, conclusions are drawn in Sec. 4.

2. Description of the model

Nuclear effects in nucleus-nucleus collisions are usually expressed through the so-called nuclear modification factor, $R_{AB}^{J/\psi}(b)$, defined as the ratio of the J/ψ yield in $A + A$ and pp scaled by the number of binary nucleon-nucleon collisions, $n(b)$. We have then

$$\begin{aligned} R_{AB}^{J/\psi}(b) &= \frac{dN_{AB}^{J/\psi}/dy}{n(b) dN_{pp}^{J/\psi}/dy} \\ &= \frac{\int d^2s \sigma_{AB}(b) n(b, s) S_{J/\psi}^{sh}(b, s) S^{abs}(b, s) S^{co}(b, s)}{\int d^2s \sigma_{AB}(b) n(b, s)}. \end{aligned} \quad (1)$$

Here $\sigma_{AB}(b) = 1 - \exp[-\sigma_{pp} AB T_{AB}(b)]$, $T_{AB}(b) = \int d^2s T_A(s) T_B(b-s)$ is the nuclear overlapping function, $T_A(b)$ is obtained from Woods-Saxon nuclear densities, and

$$n(b, s) = \sigma_{pp} AB T_A(s) T_B(b-s) / \sigma_{AB}(b), \quad (2)$$

where upon integration over d^2s we obtain the number of binary nucleon-nucleon collisions at impact parameter b , $n(b)$. The three additional factors in the numerator of Eq. (1), S^{sh} , S^{abs} and S^{co} , denote the effects of shadowing, nuclear absorption, and interaction with the co-moving matter, respectively. Let us discuss them briefly.

The nuclear absorption is usually interpreted as suppression of J/ψ yield because of multiple scattering of a $c\bar{c}$ pair within the nuclear medium. At low energies the primordial spectrum of particles created in scattering off a nucleus is mainly altered by (i) interactions with the nuclear matter they traverse on the way out to the detector and (ii) energy-momentum conservation. For $A + A$ collisions these effects can be combined into the generalized suppression factor

$$\begin{aligned} S^{abs} &= \frac{[1 - \exp(-\xi(x_+) \sigma_{Q\bar{Q}} AT_A(b))]}{\xi(x_+) \xi(x_-) \sigma_{Q\bar{Q}}^2 AB T_A(s) T_B(b-s)} \\ &\times [1 - \exp(-\xi(x_-) \sigma_{Q\bar{Q}} BT_B(b-s))] , \end{aligned} \quad (3)$$

where $x_{\pm} = (\sqrt{x_F^2 - 4M^2/s} \pm x_F)/2$, and $\xi(x_{\pm}) = (1 - \epsilon) + \epsilon x_{\pm}^{\gamma}$ determines both absorption and energy-momentum conservation. In [4] it has been found that $\gamma = 2$, $\epsilon = 0.75$ and $\sigma_{Q\bar{Q}} = 20$ mb give a good description of data. This corresponds to $\sigma_{abs} = 5$ mb at mid-rapidity and agrees well with other studies.

Secondly, coherence effects will lead to nuclear shadowing for both soft and hard processes at RHIC, and therefore for the production of heavy flavor. Shadowing can be calculated within the Glauber-Gribov theory [5], and we will utilize the generalized Schwimmer model of multiple scattering [6]. In this case the second suppression factor in Eq. (1) reads

$$S^{sh}(b, s, y) = \frac{1}{1 + AF(y_A)T_A(s)} \frac{1}{1 + BF(y_B)T_B(b-s)}, \quad (4)$$

where the main contribution to the function $F(y)$, that encodes the dynamics of shadowing, comes from the gluon rather than from the quark shadowing [7, 8]. At SPS energy the nuclear absorption dominates over the shadowing, whereas RHIC already belongs to the high-energy regime. Nuclear shadowing is non-negligible at mid-rapidity, and the combined effect of shadowing and energy-momentum conservation should be accounted for at forward rapidities. At LHC shadowing will be very strong even at $y = 0$, while energy-momentum conservation becomes a minor effect.

Finally, the processes of dissociation and recombination of $c\bar{c}$ pairs in the dense medium should be taken into account. We employ the co-movers interaction model (CIM) [9] that was recently modified to incorporate the recombination mechanism into consideration [10]. Assuming a pure longitudinal expansion and boost invariance of the system, the rate equation which includes both dissociation and recombination effects for the density of charmonium at a given production point at impact parameter s reads

$$\tau \frac{dN_{J/\psi}(b, s, y)}{d\tau} = -\sigma_{co} \left[N^{co}(b, s, y) N_{J/\psi}(b, s, y) - N_c(b, s, y) N_{\bar{c}}(b, s, y) \right], \quad (5)$$

where N^{co} , $N_{J/\psi}$ and $N_{c(\bar{c})}$ is the density of comovers, J/ψ and open charm, respectively, and σ_{co} is the interaction cross section for both dissociation of charmonium with co-movers and regeneration of J/ψ from $c\bar{c}$ pairs in the system averaged over the momentum distribution of the participants. It is the constant of proportionality for both the dissociation and recombination terms due to detailed balance $N_{J/\psi}(b, s, y) N^{co}(b, s, y) = N_c(b, s, y) N_{\bar{c}}(b, s, y)$. The solution of Eq. (5) can be approximated by

$$S^{co}(b, s, y) = \exp \left\{ -\sigma_{co} [N^{co}(b, s, y) - C(y) N_{bin}(b, s) S^{shad}(b, s, y)] \ln \left[\frac{N^{co}}{N_{pp}(0)} \right] \right\},$$

where

$$C(y) = \frac{(d\sigma_{pp}^{c\bar{c}}/dy)^2}{\sigma_{pp}^{ND} d\sigma_{pp}^{J/\psi}/dy}. \quad (6)$$

Details of the model can be found in [10]. The quantities in Eq. (6) are all related to pp collisions at the corresponding energy and are taken from experiment. Note, that the extension of the CIM to the recombination effects does not imply any additional parameters.

3. Heavy quarkonium at RHIC and LHC

The density of open and hidden charm at mid-rapidity in pp collisions at $\sqrt{s} = 200$ GeV has been reported in [11]. In the left picture of Fig. 1 we present the results of

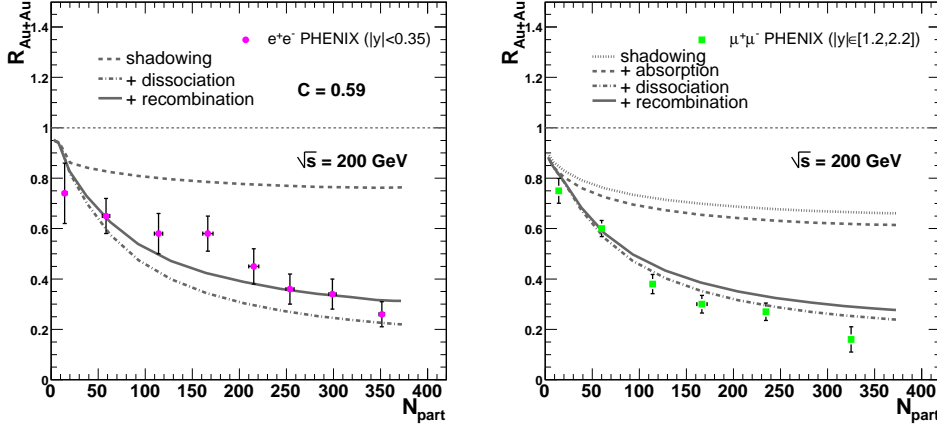


Figure 1. Results for J/ψ suppression in $Au+Au$ at RHIC ($\sqrt{s} = 200$ GeV) at mid- (left figure), and at forward rapidities (right figure). Data are from [2]. The solid curves are the final results. The dash-dotted ones are the results without recombination ($C = 0$). The dashed line is the total initial-state effect. The dotted line in the right figure is the result of shadowing. In the left figure the last two lines coincide.

our model compared to experimental data at mid-rapidity. The different contributions to J/ψ suppression are shown. Note that at mid-rapidity the initial-state effect is just the shadowing. As discussed above nuclear absorption due to energy-momentum conservation is present at forward rapidities but is negligibly small at mid-rapidity. One can see that the J/ψ suppression at forward rapidity is somewhat larger than that at mid-rapidity, in full accord with experimental data. This is due to both the recombination term and the initial-state effects. The latter are stronger for forward rapidities.

For consistency, we have also made calculations for the J/ψ suppression in $Cu+Cu$ collisions at RHIC using the same parameters as above for $Au+Au$ collisions. The results are shown in Fig. 2, and are in good agreement with the experimental data, except maybe for peripheral collisions, where the error bars are quite large. Concluding, our procedure gives a reasonable description of data both at mid- and forward rapidity for different collision systems at RHIC. The effect of recombination is more pronounced at midrapidity.

Based on our previous discussion, it is obvious that dissociation-recombination effects will be of crucial importance in $Pb+Pb$ collisions at LHC ($\sqrt{s} = 5.5$ TeV). Assuming that the energy dependence of open charm and J/ψ in pp collisions is the same (between RHIC and LHC energies), the energy dependence of the parameter C will be that of $\sigma_{pp}^{c\bar{c}}/\sigma_{pp}$. The total and differential cross section for charm can be calculated using perturbative techniques [13]. The calculations for low energies are in agreement with data, yet predictions for RHIC and Tevatron energies are lower than the data. Therefore, the extrapolation to LHC is quite uncertain. If we parameterize the energy dependence of open charm production as $\sigma^{c\bar{c}} \propto s^\alpha$, with $\alpha = 0.3$ and use the values of non-diffractive σ_{pp} as 34 mb for RHIC and 59 mb for LHC, we obtain $C = 2.5$ at LHC – a value about four times larger than the corresponding one at

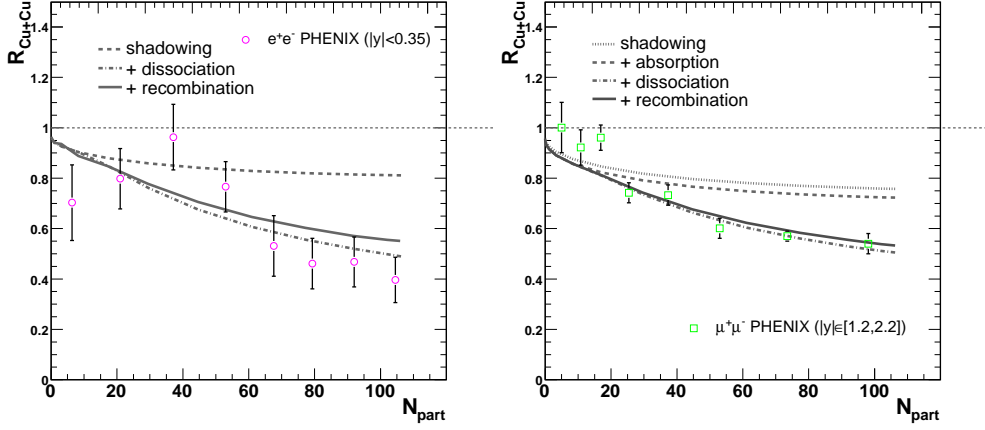


Figure 2. Results for J/ψ suppression in $Cu+Cu$ at RHIC ($\sqrt{s} = 200$ GeV), at mid- (left) and at forward rapidities (right). For details, see caption of Fig. 1. Data are from [12].

RHIC. In view of that we consider that realistic values of C at LHC are of the range 2 to 3. In Fig. 3(a) we have calculated the J/ψ suppression at LHC for several values of C , including the case of absence of recombination effects ($C = 0$). Although the density of charm grows substantially from RHIC to LHC, the combined effect of initial-state shadowing and comovers dissociation appears to overcome the effect of parton recombination. This is in sharp contrast with the findings of [14], where a strong enhancement of the J/ψ yield with increasing centrality was predicted. Note that in our approach only comovers and open charm produced at the same impact parameter as the initial J/ψ are allowed to interact, whereas models assuming global equilibrium of the produced charm with the medium allow for recombination of $c\bar{c}$ pairs from the whole volume of the fireball.

Finally, we would like to discuss the impact of initial state effects on bottomonium production. The absorptive cross section for Υ is 40-50% smaller than that for J/ψ and ψ' , and energy-momentum conservation mechanisms are pushed to higher x_F due to the large mass of the bottomonium. Therefore, nuclear absorption for Υ at LHC is expected to be quite small. The suppression of bottomonium due to gluon shadowing in Pb+Pb collisions at LHC is shown in Fig. 3(b) for several rapidities. The suppression is about 50% from mid-central to central collisions, and would be the same for all members of the Υ family. This establishes the baseline for further calculations of bottomonium dissociation and recombination in the final state.

4. Conclusions

The effects of recombination of $c\bar{c}$ pairs into J/ψ are incorporated in the comovers interaction model. These effects are negligible at low energies (SPS) due to the low density of open charm. The model does not assume thermal equilibrium of the matter produced in the collision and includes a comprehensive treatment of initial-state effects, such as shadowing, nuclear absorption and energy-momentum conservation.

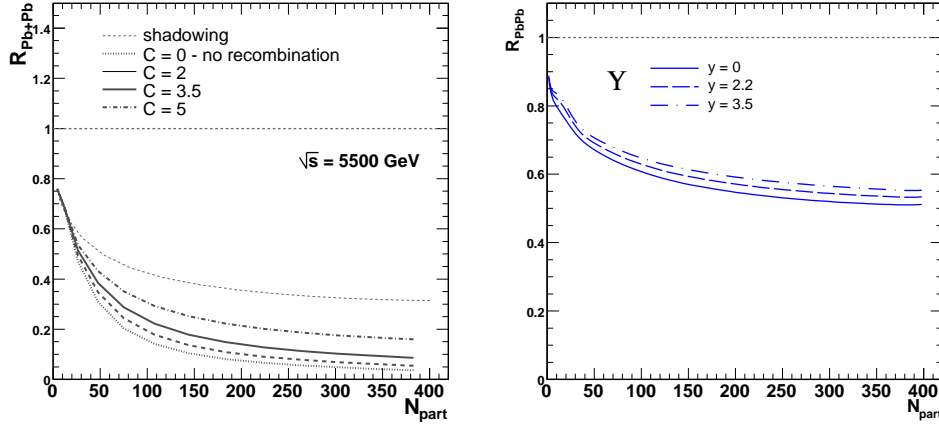


Figure 3. Left: J/ψ suppression in $Pb+Pb$ at LHC ($\sqrt{s} = 5.5$ TeV) at mid-rapidities for different values of the parameter C . The upper line is the suppression due to initial-state effects (shadowing). Right: Centrality dependence of Y suppression due to gluon shadowing in $Pb+Pb$ collisions at $\sqrt{s} = 5.5$ TeV.

In our approach, the magnitude of the recombination effect is controlled by the total charm cross section in pp collisions. Using it as an input, the centrality and rapidity dependence of experimental data is reproduced both for $Au+Au$ and $Cu+Cu$ collisions at full RHIC energy. For LHC we are lacking the experimental information and should rely on estimates from theoretical models. For a reasonable choice of parameters, we predict that the suppression observed at RHIC and lower energies will still dominate over the recombination effects. This is due to the large density of comovers and to the strong initial-state suppression at these ultra-relativistic energies.

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